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Efficiently estimating some common geostatistical models from «image-type, possibly incomplete» datasets: CGEMEV and its extension to unknown nugget-effect

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The problem of estimating the 2 parameters ("**range**" and "**variance**") of a stationary isotropic Gaussian process whose autocorrelation function belongs to the Matérn class, appears in many contexts (e.g. [9,11]). We propose two extensions of the CGEM-EV method (cf. [5,6]) for the important case of **unknown "nugget-variance"** (3rd parameter), and compare them to the classic maximum likelihood (ML) method, for the Matérn subclass $\nu = 1/2$, and "small image"-type observations

Background

We mainly consider the following statistical model which arises e.g. in remote sensing image analysis: let $Z(\mathbf{s})$, $\mathbf{s} \in \mathbb{R}^2$, be a zero mean stationary Gaussian stochastic process whose autocorrelation function is assumed to belong to the popular isotropic Matérn family. One realization of this process is observed at n sites $\mathbf{s}_i, i = 1, \cdots, n$, which are a **subset** of the $n_1 \times n_2$ regularly spaced locations $\bar{\mathbf{s}}_k$ in $[0,1] \times [0,1]$, with an additive Gaussian white noise whose variance is σ_0^2 (this noise can model either suspected homoscedastic measurement errors or a nugget effect added to Z, see e.g. Zhang and Zimmerman (2007) and references therein). Using a standard lexicographic ordering, the observations thus form a vector $\boldsymbol{y}$ of size n whose law is Gaussian :

$$\boldsymbol{y} \sim \mathcal{N}(\mathbf{0}, \tau_0^2 \boldsymbol{R}(\theta_0) + \sigma_0^2 \boldsymbol{I}_{n,n}) \text{ where } \boldsymbol{R}(\theta) = \boldsymbol{J}_{n,n_1\times n_2} \tilde{\boldsymbol{R}}(\theta) \boldsymbol{J}_{n,n_1\times n_2}^T$$

with $\boldsymbol{J}_{n,n_1\times n_2}$ denoting the rectangular, "with coefficients $\in \{0,1\}$", incidence matrix, $\boldsymbol{I}_n$ the identity matrix, and $\tilde{\boldsymbol{R}}(\theta)$ the autocorrelation matrix of the gridded process i.e. the block Toeplitz matrix (with n_1^2 Toeplitz square blocks, each of size $n_2 \times n_2$) whose coefficients are given by

$$\left[\tilde{\boldsymbol{R}}(\theta)\right]_{j,k} := \rho_{\nu,\theta}(||\bar{\mathbf{s}}_j - \bar{\mathbf{s}}_k||), \ j,k = 1, \cdots, n_1 \times n_2,$$

$||\cdot||$ being the Euclidean norm and $\rho_{\nu,\theta}$ the Matérn function

$$\rho_{\nu,\theta}(x) = \frac{(\theta x)^\nu}{\Gamma(\nu) 2^{\nu-1}} K_\nu(\theta x), \quad x > 0, \ \theta > 0,$$

where K_ν is the modified Bessel function of the second kind of order $\nu > 0$.

We here use the parameters b, θ, σ, with $b_0 = \frac{\tau_0^2}{\sigma_0^2}$ called the true signal-to-noise (SNR). The **microergodic-parameter** is $c = b\sigma^2\theta^{2\nu}$.

In all the alternatives to ML we consider, the signal-variance τ_0^2 is "estimated", **given a candidate value for the noise-variance** σ^2, by the naive "bias corrected" **empirical variance** :

$\hat{\tau}^2_{\mathrm{EV}|\sigma} := n^{-1}\boldsymbol{y}^T\boldsymbol{y} - \sigma^2$ (and the "SNR estimate" is $\hat{b}_{\mathrm{EV}|\sigma} := \frac{\hat{\tau}^2_{\mathrm{EV}|\sigma}}{\sigma^2}$).

Proposed estimators VEZ and LE$_3$

When the true $\sigma_0{}^2$ is known, CGEM-EV$|\sigma_0$ (which stands for "Conditional Gibbs-Energy Mean and Empirical Variance") is quite efficient, both statistically and computationally (using a fast randomized-trace), for many common problems (see [5,6]). Recall that CGEM-EV$|\sigma$ consists of solving (a fixed-point algorithm is used in [2,3,4,7]) the equation in θ defined by

$$\mathrm{LE}_1\left(\theta \left| \hat{b}_{\mathrm{EV}|\sigma}, \sigma\right.\right) = 0 \quad \text{with} \quad \mathrm{LE}_1(\theta|b,\sigma) := \frac{1}{n}\left\langle \boldsymbol{A}_{b,\theta}\,\mathbf{y}, \boldsymbol{R}(\theta)^{-1}\boldsymbol{A}_{b,\theta}\,\mathbf{y}\right\rangle - b\,\sigma^2\,\frac{1}{n}\,\mathrm{tr}(\boldsymbol{A}_{b,\theta}) \qquad (1),$$

where the "smoothing matrix" $\boldsymbol{A}_{b,\theta} := b\,\boldsymbol{R}(\theta)\,(b\,\boldsymbol{R}(\theta) + \boldsymbol{I})^{-1}$ (a.k.a. a Kalman smoother); let us denote "the" root of (1) with $\sigma = \sigma_0$ (the smallest one in case of multiple roots) by $\hat{\theta}_{\mathrm{CGEMEV}|\sigma_0}$.

- The first extension of CGEM-EV to the case of unknown σ_0 is a simple (and fast!) "plugin" method: one computes a nonparametric estimator of σ^2, say $\hat{\sigma}^2_{\mathrm{VEZ}}$, by **extrapolating at 0_+ the (classic or robust) semi-variogram function as a function of the lag** (proposed by [9]) and substitutes $\hat{\sigma}^2_{\mathrm{VEZ}}$ for $\sigma_0{}^2$ in the CGEM-EV$|\sigma_0$ equation in θ, producing $\hat{\theta}_{\mathrm{CGEMEV}|\hat{\sigma}_{\mathrm{VEZ}}}$.

- The second possible extension consists of **adding to (1) a well-known equation satisfied by the ML estimate of σ^2** when the signal-to-noise ratio b and θ are fixed; precisely, σ is the root of

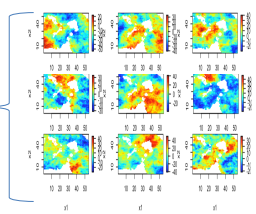
$$\mathrm{LE}_3(\sigma|b,\theta) := \frac{1}{n}\left\langle \mathbf{y}, (\boldsymbol{I} - \boldsymbol{A}_{b,\theta})\,\mathbf{y}\right\rangle - \sigma^2 \quad (2).$$

N.B. : In fact **LE$_3(\theta|b,\sigma)$** (resp. LE$_1(\sigma|b,\theta)$) **is proportional to the partial derivative of the log-likelihood w.r.t. the 3rd** (resp. 1st) **parameter**.

A classic bisection-search of σ, can be used to solve the concentrated CGEM-EV-LE$_3$ equation $\mathrm{LE}_3\left(\sigma\left|\hat{b}_{\mathrm{EV}|\sigma}, \hat{\theta}_{\mathrm{CGEMEV}|\sigma}\right.\right) = 0$ in σ, where an inner iteration is used to compute $\hat{\theta}_{\mathrm{CGEMEV}|\sigma}$. The final $\hat{\theta}$-iterate, thus root of (1) and (2), will be denoted by $\hat{\theta}_{\mathrm{CGEMEVLE}_3}$.

Experiments setting, VEZ-tuning

- $\nu = 1/2$
- $n_1 = n_2 = 54$. about 20% missing data (fixed locations) : n=2300
- signal-to-noise ratios b_0 $\left(= \frac{\mathrm{var}(Z)}{\mathrm{var}(\epsilon)}\right)$ chosen among: $7^2, 10^2, 15^2, 33^2$
- For each b_0 , inverse-range parameter $\theta_0 = 1, 3, 6, 12, 24, 48$

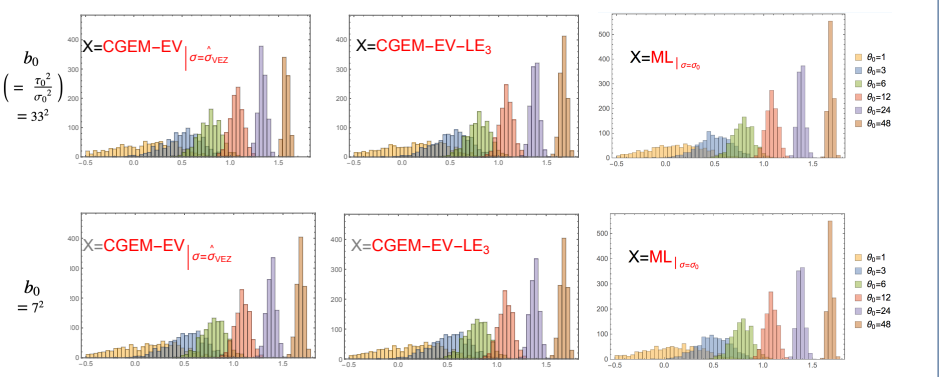


6 replicates for $\theta_0 = 3$, $b_0 = 15^2$

We use the "best performing" VEZ pour this setting, precisely:
- classic variogram,
- maximum-lag := 3/54

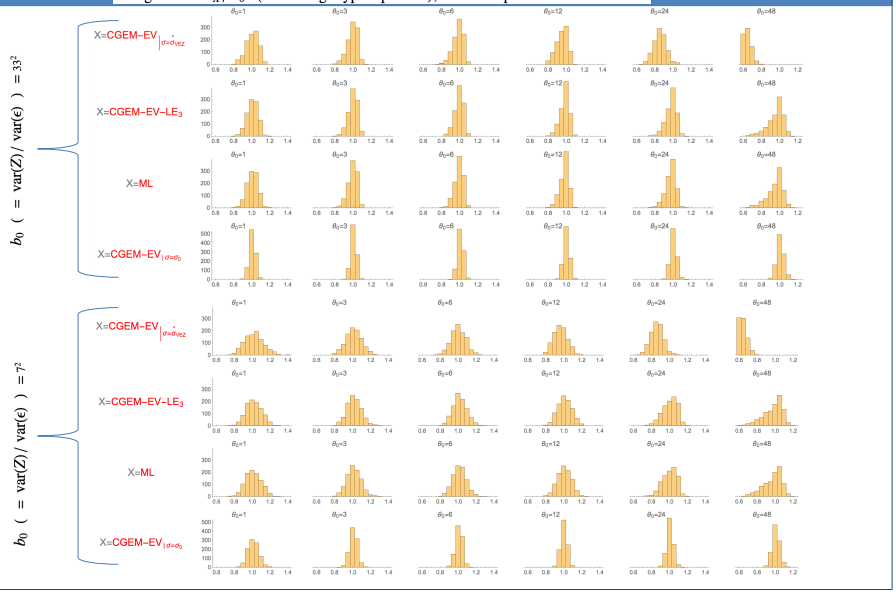
Estimation of the inverse-range parameter θ_0 .

histograms of $\log_{10}(\hat{\theta}_X)$ (1000 image-type replicates), observed pixels number n=2300



Estimation of the micro-ergodic parameter c_0

histograms of $\hat{c}_X / c_0$ (1000 image-type replicates), observed pixels number n=2300



Conclusions

- Concerning the estimation of the range-parameter θ_0, estimating the nugget-variance via CGEM-EV-LE$_3$ only causes a very small additional inaccuracy, even when compared with "ML given the true σ_0". The simplest CGEMEV $|\hat{\sigma}_{\mathrm{VEZ}}$ is almost as good, except for the largest θ_0's.

- Concerning the estimation of the micro-ergodic-parameter $c_0 = b_0\,\sigma_0^2\,\theta_0^{2\nu}$, CGEMEV $|\hat{\sigma}_{\mathrm{VEZ}}$ is clearly not efficient for the two largest θ_0's (and also for $\theta_0 \geq 6$, in case of strong SNR). But CGEM-EV-LE$_3$ is always nearly as efficient as ML (also note that the ideal "ML given the true σ_0" would much better estimate c_0) .

The R-package CGEMEV can efficiently compute $\hat{\theta}_{\mathrm{CGEMEV}|\sigma}$ for much larger image-type data (any product $\boldsymbol{A}_{b,\theta}\,\mathbf{x}$ using a fast, matrix free, preconditioned iterative algorithm, like FSAI-PCG) : → ongoing work is an assessment [1] of various versions of the "bisection, with inner iterations" mentioned above for computing $\hat{\theta}_{\mathrm{CGEMEVLE}}$.

this poster

github.com for R-package

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